Properties of Particleboards Produced from Various Lignocellulosic Particles

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This study investigated the possibility of using chips obtained from annual plants as substitutes for pine chips in the external layers of boards intended for the building and furniture industries. The tested materials included rape, rye, triticale, reed, and corn straw, as well as pine chips. Three-layer boards were produced with the core layer made from pine chips and the external layers from different annual plants. The chips were glued with 4% polymeric diphenylmethane diisocyanate (pDMI) for all layers. The boards were tested for their modulus of rigidity, modulus of elasticity, internal bond, swelling, water absorption, and strength after being subjected to the cooking test. The results showed that in specific conditions, all annual plants may serve as partial substitutes for pine chips in the external layers of particleboards. The presence of these materials was particularly favorable for the modulus of elasticity. Corn straw was the most useful, as the boards supplemented with the material met the requirements of the EN 312 (2010) standard in terms of mechanical properties and water resistance for P5 boards and therefore it can be used in the building industry.

Keywords: Annual plant particles; Mechanical properties; Particleboards

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INTRODUCTION

Substituting natural wood in the production of particleboards has gained increasing attention. This interest is triggered by the constantly rising prices of wood (on average 3% a year), limited availability of high quality wood, and strong market competition that affects the costs of wood-based materials. Wood can be replaced with other fibrous materials, such as crop plants, cereal residues after threshing, and other annual plants (Grigoriou 2000; Mo *et al.* 2003). Although the idea of using these plants for manufacturing wood-based particleboards is not new (first attempts were made in 1960s), the diverse anatomical structure and other specific properties of these materials have rendered the boards unsuitable for mass production.

According to various sources, the annual surplus of straw production in Poland is about 8 to 13 million tons after deducting the consumption for bedding and fodder. The most widely available straws in Poland are cereal straw (73.5%) and rape straw (9.1%) (Gradziuk 2014). Rape straw seems especially interesting, as it is not useful for any agrotechnical purposes or feeding. This means that it must be managed in a different way.

Despite numerous research reports on the use of various lignocellulosic materials in the manufacturing of particleboards, few of them meet the requirements for raw materials intended for the production of boards used in the building industry. This is due to their structure, chemical composition, and particle size that differ considerably from wood. The most recent attempts at using these materials include oriented strand boards (OSB) supplemented with the straw of various cereal species (Wasylciw 2001), OSB made of wheat straw alone (Han *et al.* 2010; Cheng *et al.* 2013), OSB with a core layer made of rape straw (Mirski *et al.* 2016), particleboards made of wheat straw (Zheng *et al.* 2003; Boquillon *et al.* 2004; Bekhta *et al.* 2013; Hafezi and Hosseini 2014), rape straw (Dziurka and Mirski 2013; Huang *et al.* 2016), white mustard (Dukarska *et al.* 2015), rice straw (Li *et al.* 2010; Zheng *et al.* 2014; Kurokochi and Sato 2015), corn straw (Zheng *et al.* 2014; Wu *et a*l. 2015), and medium-density fiberboards (MDF) enriched with fibers from corn or cotton stalks (Kargarfard and Jahan-Latibari 2011).

These raw materials are an attractive alternative to wood due to the numerous useful product properties of which they are the main components. For example, they provide lower hygroscopicity, better thermal (Pinto *et al*. 2011) and acoustic insulation (Faustino *et al.* 2012), lower specific gravity (Pinto *et al*. 2012), and are much less expensive than wood.

As mentioned above, the investigated annual plants have already been researched and confirmed as quality substitutes for wood chips. However, the boards were manufactured in highly variable conditions, which made comparisons difficult. Therefore, the aim of this study is to identify the annual plants that could substitute pine chips in the external layers of boards intended for the building and furniture industries.

EXPERIMENTAL

Three-layer boards were manufactured from industrial pine chips (Swiss Krono, Żary, Poland) as internal layer and particles (chips) of annual plants. The latter were obtained by shredding their straw in a laboratory shredder. The control board were three-layer pine chips boards. The boards were marked according to the material of their external layer and the following symbols were used:

- Ra – rape straw chips (*Brassica napus* L. *var. napus*);
- Tr – triticale straw chips (*Triticosecale* Witt.);
- Ry – rye straw chips (*Secale* L.);
- Co – corn straw chips (*Zea mays* L.);
- Re – reed stalk chips (*Phragmites vulgaris* Samp.);
- Pi – pine chips (*Pinus sylvestris* L.);

Table 1. Fractional Composition of the Investigated Materials

Mesh Size	Material					
	Ra	Tr	Ry	Co	Re	Pi
(mm)	Sieve Residue (%)					
6.3	0.8	2.7	7.4	7.2	6.2	7.2
5	2.0	4.1	7.0	11.2	9.8	7.5
4	5.8	8.2	7.1	11.1	8.7	7.9
2.5	56.4	47.3	37.6	32.9	41.8	36.3
1	32.7	35.3	36.7	31.0	32.1	35.0
0.5	1.5	1.7	3.1	4.2	1.0	4.5
< 0.5	0.8	0.7	1.2	2.3	0.4	1.6

After shredding, the particles were screened using a two-screen sorter, with mesh sizes of 15 × 15 mm^2 and 0.5 × 0.5 mm^2, to separate long strands from dust and short strands. The desired fraction was the particle content left on the screen with a mesh size of 0.5 × 0.5 mm^2. The material was then subjected to a sieve analysis. The greatest percentage share of chips retained on the screen was with a mesh size of 2.5 × 2.5 mm^2, and the second most abundant was the fraction retained on a 1.0 × 1.0 mm^2 screen (Table 1).

The fractions left on these screens constituted 89.1, 82.6, 74.3, 63.9, 73.9, and 71.3% weight share for rape, triticale, rye, corn, reed, and pine chips, respectively. Corn straw was the only material that contained more large-dimension particles than pine chips. However, it was also the most variable material in terms of particle size (Table 2), and it had the highest width coefficient (Table 3).

Table 2. Mean Dimensions of Lignocellulosic Particles Used for Board Manufacturing

Parameter	Material					
	Ra	Tr	Ry	Co	Re	Pi
	Linear Parameter (mm)					
Length- L_{ave}	14.06	18.26	16.81	16.05	18.21	13.72
L_{max}	33.57	42.97	41.37	34.51	49.2	38.43
L_{min}	6.14	7.12	4.92	7.3	8.35	6.05
Width- W_{ave}	2.18	2.55	1.70	1.43	2.19	2.03
W_{max}	3.78	4.01	2.78	3.62	4.32	3.20
W_{min}	0.52	1.01	0.39	0.08	0.83	1.22
Thickness- T_{ave}	0.62	0.30	0.25	0.46	0.55	1.04
T_{max}	1.63	0.96	0.63	1.35	1.30	1.89
T_{min}	0.09	0.02	0.05	0.05	0.15	0.24

Table 3. Basic Characteristics of the Particles Used for Manufacturing of Lignocellulosic Boards

Material	Slenderness	Width Coefficient	Flatness	Bulk density, kg/m^3
Ra	22.8	6.5	3.5	79.2±2
Tr	61.0	7.2	8.5	60.1±1.2
Ry	68.6	9.9	6.9	62.8±2.3
Co	34.9	11.2	3.1	64.2±3.4
Re	33.2	8.3	4.0	87.4±2.7
Pi	13.2	6.8	2.0	131.7±1.9

As the dominant fraction share was similar in all boards, the chips were glued with the same amount of pDMI (4% of dry weight) for all layers and board types. The material intended for the external layers was dried up to 9% moisture content and the material for the core layer up to 6%. The proportion of external to core layers was 1:1. Pressing conditions were as follows: temperature of hotplates was 200 °C, the maximum pressure was 2.5 N/mm^2, a pressing time of 18 s/mm of board thickness, a board thickness of 15 mm, and a density of 625 kg/m^3.

The boards produced in this way were tested against relevant standards, and the following characteristics were assessed: the static bending strength (modulus of rigidity

(MOR)) and the modulus of elasticity (MOE) according to EN 310 (1993); internal bond (IB) according to EN 319 (1993); thickness swelling (TS) as per EN 317 (1993) and water absorption (WA) during determination of swelling; and lastly the strength after cooking test V100 according to EN 1087-1 (1995).

Statistical analyses of the data were performed with Statistica 12.0 software (StatSoft Inc., Tulsa, OK, USA), and to analyse the data Levene's test was used.

RESULTS AND DISCUSSION

The MOR was strongly correlated with the type of material forming the board mat (Fig. 1). The lowest MOR was reported for reed boards, and it was 2.4 N/mm^2 lower than that of pine boards. No significant differences in the modulus of rigidity were observed between pine boards and those boards manufactured from rape and corn chips; however, the MOR was over 10% higher in corn *vs.* rape boards. The greatest bending strength was noticed in the rye and triticale boards (28.7 and 25.3 N/mm^2, respectively), which was 174% and 153% higher than in pine board, respectively.

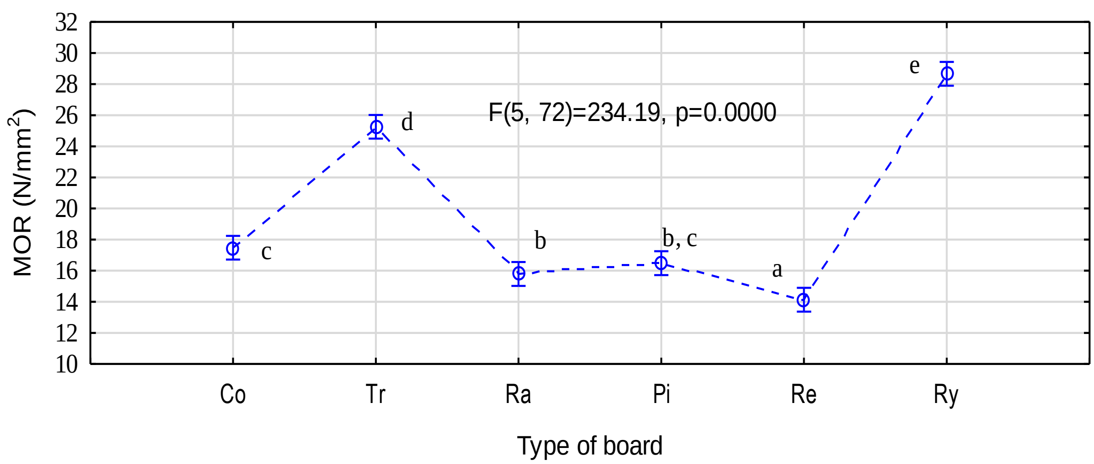

Fig. 1. Bending strength in boards made from different materials

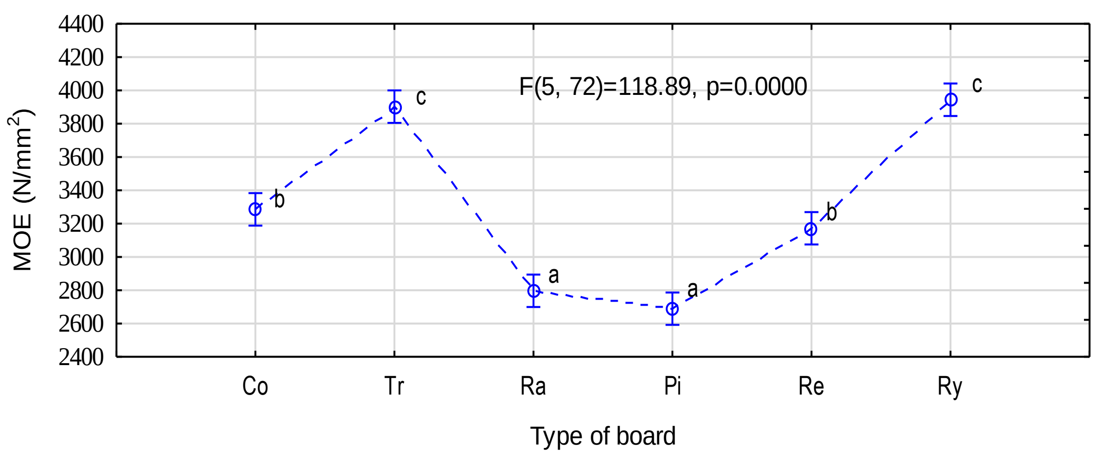

Fig. 2. Modulus of elasticity in boards made from different materials

All boards containing straw particles exhibited a higher MOE than the control pine board, as shown in Fig. 2. Although there were no significant differences in the modulus of elasticity for rape straw board and pine board, the MOE for rape board was 5% higher than that determined for pine board. The modulus of elasticity for corn and reed boards was similar and it was 20% higher than that of the control board. Similarly, for MOR, the boards made of rye and triticale had also the highest MOE. The values were similar and over 50% greater than those for pine board.

The highest internal bond was noticed in pine board, as it was nearly two times greater than recommended for P5 boards in the EN 312 (2010) standard (Fig. 3). Of the boards made from annual plants, the highest IB was reported for those made from corn particles. Although its strength was one third lower than that of the pine board, it was still approximately 70% higher than in rye and triticale boards and also met the requirements of a relevant standard (0.45 N/mm^2 as per EN 312 (2010)).

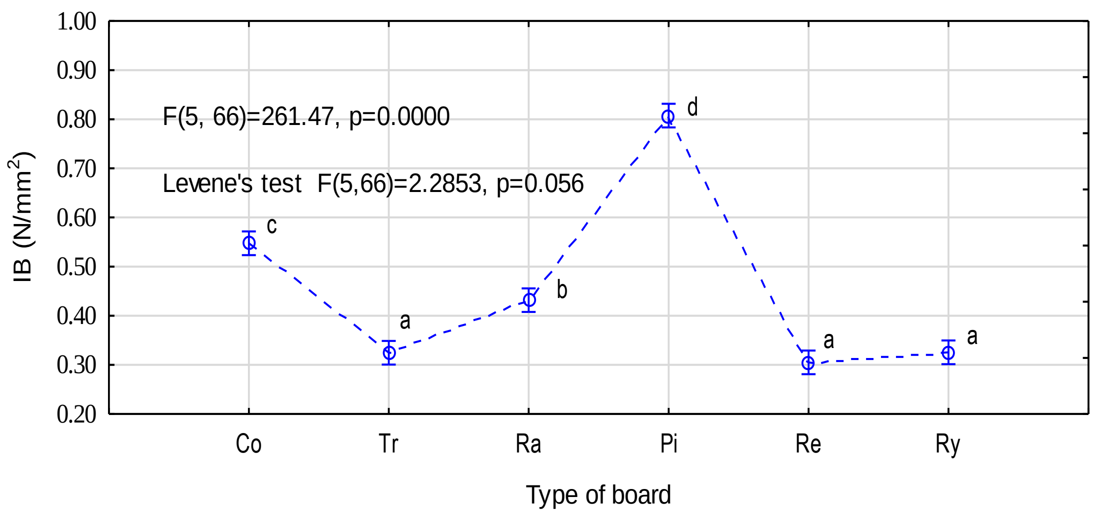

Fig. 3. Internal bond in boards made from different materials

Swelling and WA after 24 h of soaking in water was lower for all straw boards, except for the WA of rape board (Table 4).

Table 4. Hydrophobic Properties of Boards Made from Annual Plants

Board Type	WA		TS		**V100** After Cooking Test	
	%				N/mm^2	
Ra	101	*3.2**	35.7	*7.3*	0.06	*7.0*
Tr	76	*4.5*	25.8	*5.3*	0.09	*5.9*
Ry	71.1	*6.5*	22.2	*5.7*	0.06	*15.7*
Co	86.5	*3.4*	26.3	*3.8*	0.16	*9.8*
Re	66.6	*4.2*	28.8	*3.8*	0.05	*16.3*
Pi	97.2	*1.6*	38.4	*5.6*	0.18	*7.7*

* - Coefficient of variation

The lowest water absorption was observed for reed, rye, and triticale boards (66.6%, 71.1%, and 76.0%, respectively). Rye and triticale straw had the highest slenderness coefficient. This was because particles of these straws were long and thin, which limited water absorption and swelling. Accordingly, the boards made from rye and triticale straw showed the lowest swelling at 22.2% and 25.8%, respectively. This parameter in the control board was 38.4% (*i.e.*, 40% higher). The greatest tensile strength was determined for the pine chips (0.18 N/mm^2) board after the cooking test. The second strongest was corn straw board (0.16 N/mm^2), with the tensile strength reaching 88% of the control group. Therefore, both boards met the requirements for load bearing boards in humid conditions (P5 as per EN 312 (2010)). The lowest tensile strength following the cooking test was observed for reed (0.05 N/mm^2) and the rape and rye straw boards (0.06 N/mm^2).

CONCLUSIONS

1. All investigated annual plants may serve as partial substitutes of pine chips in the external layers of particleboards.
2. The use of annual plant chips in the external layers favorably affected the modulus of elasticity, as it was considerably higher in all experimental boards *vs.* the control ones.
3. All experimental boards were characterized by a much smaller swelling as compared with the pine board, which was primarily the result of their naturally higher hydrophobicity.
4. The boards made from corn straw were the most useful, as they met the requirements of EN 312 (2010) standard in terms of mechanical properties and water resistance assessed by the V100 test for P5 boards and could be used in the building industry.

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